6

PROTOTYPING THE PHYSICAL DESIGN

AS YOU SAW in the earlier chapters, one of the reasons that the Internet of Things is such an exciting area is that it cuts across so many different disciplines. It involves software, electronics, experience design, and product design.

It's this last field, product design, that seems to be the stumbling block for many a nascent Internet of Things project, judging by the number of technically brilliant creations gracing the pages of the Hackaday website or Kickstarter that are left as bare circuit boards or crammed into whatever box came to hand. If the Internet of Things is to succeed in reaching mass appeal, this lack of design is something we need to change. If you're a designer, give yourself a pat on the back; we need more people like you involved. If you're not a designer, don't worry; in this chapter we explore some of the techniques and tools to help get you started.

PREPARATION

To best prepare for design work, you should (in an ideal world) start long before you even have a particular problem to solve; developing an interest in design and having examples of design ideas you like are part of an ongoing process. Luckily, though, if you haven't already started this preparation, there's no better time than now. Even better, the process doesn't really look like work and might even become something that you class as fun!

All you need to do is develop an interest in the world around you and start paying attention to the wealth of objects and experiences that you encounter. This first step will help you work out what you like and what you don't like. Over time, you'll start to work out which qualities you particularly appreciate. Maybe you are attracted to the crisp, sleek lines of your Colnago road bike, or you admire the perfect balance of your 8-inch chef's knife, or you smile at the way your MacBook's MagSafe charger snaps into location. All such observations will help you work out what, for you, makes a good design.

Naturally, the more of the world you encounter, the more source material you'll have to work with. We're not suggesting that your accountant will let you get away with expensing your foreign holidays, but the exposure to different cultures and environments would help keep your critical faculties sharp. An easier sell, however, might be the occasional ticket to a gallery or museum, particularly those with a design slant or relevant exhibition. Who knew that *professional development* could be so enjoyable?

As you go, collect details about the items that inspire you. Take photos, jot down things in your notebook, or sketch them out. Paste them into an old-school scrapbook. Save them to Tumblr or Pinterest or your blog. Whatever works best for you. Over time you'll build up an archive of good design that will help you spark your creativity when designing things of your own.

The other side to a (very) basic design education is an understanding and appreciation of the tools available and the *materiality* of the processes involved in making things in the physical, rather than the digital, realm.

Items crafted in the digital world can focus exclusively on appearances and take on any form they like; in the real world, those pesky laws of physics and the limitations of the tools for fabrication come into play. That majestic overhang might look lovely in your 3D design package but would shift the centre of gravity of your chair such that it falls over when built. And those crisp 90-degree corners limit your options for making that housing—removing the former would be nearly impossible when trying vacuum forming, and it would complicate the injection moulding process.

A Note on Tools

Depending on how good (and for some of the tools how recent) your education was, you may not have any experience using some of the tools we've mentioned here. If you aren't an engineer, it's quite likely that you won't really know what they do or when to use them.

We'll cover laser cutters, 3D printers, and CNC mills later in the chapter, but we won't be looking at lathes or vacuum formers in detail.

Lathes tend to come in two main forms, depending on whether they're to be used for wood-work or metal-work. However, both types work in the same manner: the workpiece is held in a chuck which allows a motor to spin it along one axis. This then allows a cutter to be brought to bear on the spinning material, cutting it into the desired shape. As a result of this rotation around an axis, it produces good results for work that has a symmetry around an axis of rotation.

Another way to think of it is a bit like the inverse of a drill. Whereas drilling involves bringing a rotating tool to bear on a static workpiece, the lathe lets you bring a static tool into contact with a rotating workpiece.

Vacuum forming is an easy way to make thin plastic shells by sucking them onto a mould. A sheet of plastic is heated in a frame until it is very soft and pliable. Then the form or mould that provides the shape for the finished item is pushed into the softened plastic and a vacuum applied to help suck the plastic tight against the mould while it sets. It isn't suitable for particularly detailed or very deep moulding, but once the mould is created, pieces can be churned out quite quickly, even for manually operated machines.

As with most things, the more experience you gain with different materials and tools, the better your understanding will be when you come to design something. This is another great argument for seeking out and joining your local hackspace or makerspace. Most of them have tools that you wouldn't necessarily be able to afford on your own, such as laser cutters or 3D printers, and many have other machines, such as CNC mills, lathes, or vacuum formers. All of them have a wealth of expertise that you can tap into, in the form of the community of members.

So, whilst waiting for inspiration to strike, start playing around with the tools you've got to hand. Get involved in local (or not so local) hackdays; make things to give as gifts (or just to see what happens). By way of example, in the past month the members of DoES Liverpool (the makerspace that we helped found) have laser cut a (scaled down) woolly mammoth skeleton out of birch plywood, 3D-printed a replacement for a lost chess piece, and experimented with cutting some woollen felt into robot shapes in the laser cutter.

SKETCH, ITERATE, AND EXPLORE

Doing a lot of preparatory work doesn't mean that you won't do additional exploration and gathering of possible starting points when you do finally sit down with a specific project in mind. Arguably, in the early stages of a design, you can never do too much iterating through ideas and trying out different approaches to solving the problem.

Although a lot of this chapter is about the new digital fabrication tools—such as 3D printers and CNC machines—which let you produce small runs or one-offs that still look professional, we're going to start with a look at some much lower-tech solutions.

You might be tempted to fire up your 3D design package as soon as you sit down to design something. However, your first idea is unlikely to be the best, so you should be optimising for speed of iteration rather than quality of prototype. You could iterate through designs with a 3D printer, but doing so with a pen and paper is much quicker.

To begin with, you're looking for a broad search across the problem area. The objective is to get to grips with as many aspects of the design as possible, rather than drilling down into one specific possible result.

Pushing beyond the obvious solutions forces you to look at things differently and increases the likelihood that you'll have a good design among your options.

Use whatever tools make most sense to help with the idea generation and exploration. You might use a mood board—a whiteboard where you jot down thoughts and sketches over a few days—or a notebook that you doodle sketches in while sitting on a park bench watching the world pass by.

By now, some of you may be protesting, "That's all very well, but I can't draw!" This is much less of a problem than you might think. The sketches aren't for an art gallery; they're to help you work through your thinking. They only need to capture and convey your ideas. The more sketching you do, the better they will get. But ultimately, if the full extent of your abilities is stick men, just carry on drawing stick men and don't worry about it.

If the idea warrants it (and maybe even if it doesn't), don't be afraid to take your sketching into three dimensions. Mock up different designs with modelling clay or LEGO or some of the other methods we cover in this chapter. Try out different sizes and see how the changes in dimensions affect the feel or the look of the design.

Maybe even combine the approaches here with the things you learnt in Chapter 5 for prototyping the software and electronics and lash up a rough-and-ready prototype that you can try out properly. Then give it or show it to some of the people who might use the finished item to find out how they interact with it.

The key lesson is to use these techniques to experiment with different possibilities and learn which features of which designs are best. This approach allows you to synthesize the results into a coherent final design.

Consider, for example, the evolution of the design for the Good Night Lamp (which we featured in a case study in the last chapter). The original design was a more traditional lamp shape, but in a design workshop, the team batted around a range of ideas with the help of a purely functional prototype. They realised that a design echoing the shape of a house better conveyed the core concept of connecting loved ones in their homes.

The evolving design for the Good Night Lamp (from left to right): original design; functional mockup; redesign mockup; redesign functional prototypes (orange and wood/acrylic); revised size mockup; revised size functional prototype.

After the workshop, the new design was mocked up in laser-cut acrylic and plywood before functional prototypes were made in acrylic and veneered medium-density fibreboard (MDF) with a CNC milling machine.

After living with the redesign for a few weeks, they realised that the prototypes were a little bit large. More mockups followed, this time cut by hand in plywood, to try out different sizes. With the right size chosen, they milled out and assembled a new set of functional prototypes. The revised sizing has proven much better and forms the basis of the design for the first production run.

Now that we've covered some of the more general approaches to working through your design, we can dig deeper into some of the specific techniques to realise a prototype.

NONDIGITAL METHODS

We've already seen how pen and paper remain essential tools in the designer's arsenal, but they aren't the only ones to have survived the digital revolution. Many of what could be deemed more traditional craft techniques are just as valid for use when prototyping the physical form of your device.

One of the key advantages that these techniques have over the newer digital fabrication methods is their immediacy. Three-dimensional printing times are often measured in hours, and although laser cutting is much faster, performing a cut still takes minutes. And all this is without including the time taken to revise the design on the computer first.

Compare that to the speed with which you can reconfigure a model made from clay or from LEGO—and that isn't just down to the hours of practice you put in while you were growing up! Keeping the feedback loop as short as possible between having an idea and trying it out frees you up for more experimentation.

Let's look at some of the more common options here:

- **Modelling clay:** The most well-known brands are Play-Doh and Plasticine, but you can find a wealth of different versions with slightly different qualities. Some, like Play-Doh, have a tendency to dry out and crack if left exposed to the air. Plasticine doesn't suffer from this problem, but as it remains malleable, it isn't ideal for prototypes which are going to be handled. Modelling clay is best used for short-term explorations of form, rather than longer-term functional prototypes.
- **Epoxy putty:** You might have encountered this product as the brand Milliput; it is similar to modelling clay although usually available in fewer colours. It comes in two parts, one of which is a hardener. You mix equal parts together to activate the epoxy. You then mould it to the

desired shape, and in about an hour, it sets solid. If you like, you can then sand it or paint it for a better finish, so this product works well for more durable items.

- **Sugru:** Sugru is a mouldable silicone rubber. Like epoxy putty, it can be worked for only a short time before it sets (about 30 minutes, and then about a day to fully cure); but unlike epoxy, once cured, it remains flexible. It is also good at sticking to most other substances and gives a soft-touch grippy surface, which makes it a great addition to the designer's (and hacker's) toolkit.
- **Toy construction sets:** We've already mentioned the ubiquitous LEGO sets, but you might also consider Meccano (or Erector Sets in the United States) and plenty of others. If you're lucky, you already have some gathering dust in the attic or that you can borrow from your children. The other interesting feature of these sets is the availability of gears, hinges, and other pieces to let you add some movement to your model. You can purchase systems to control LEGO sets from a computer, but there's no requirement for you to use them. Many hackers combine an Arduino for sensing and control with LEGO for form and linkages, as this provides an excellent blend of flexibility and ease of construction.
- **Cardboard:** Cardboard is cheap and easy to shape with a craft knife or scissors, and available in all manner of colours and thicknesses. In its corrugated form, it provides a reasonable amount of structural integrity and works well for sketching out shapes that you'll later cut out of thin plywood or sheets of acrylic in a laser cutter (a topic we return to when we look at laser cutting later in the chapter).
- **Foamcore or foamboard:** This sheet material is made up of a layer of foam sandwiched by two sheets of card. It's readily available at art supplies shops and comes in 3mm or 5mm thicknesses in a range of sizes. Like cardboard, it is easily cut with a craft knife, although it is more rigid than corrugated cardboard. There are also specialist foamboard craft knives which allow easy 45-degree cuts for mitred edges and have two blades—spaced 3mm apart—which make it trivial to cut slots into which you can insert another sheet of foamboard to generate three-dimensional shapes. For an excellent primer in working with foamcore, see `http://www.paulos.net/teaching/2011/BID/assignments/Foamcore_construction.pdf`.
- **Extruded polystyrene:** This product is similar to the *expanded* polystyrene that is used for packaging but is a much denser foam that is better suited to modelling purposes. It is often referred to as "blue foam", although it's the density rather than the colour which is important. Light yet durable, it can be easily worked: you can cut it with a craft knife, saw it, sand it, or, for the greatest ease in shaping it, buy a

hot-wire cutter. Sheets of extruded polystyrene are much thicker than foamboard, usually between 25mm and 165mm. As a result, it is great for mocking up solid three-dimensional shapes. If you need something thicker than the sheet itself, you can easily glue a few layers together. The dust from sanding it and the fumes given off when cutting it with a hot-wire cutter aren't too nice, so make sure you wear a dust mask and keep the area ventilated when working with it.

Having reviewed the sorts of techniques which you learnt when your design education started, back in primary school, we can move on to looking at some of the newer tools. Like most aspects of modern life, computers have also swept through manufacturing, opening new possibilities in rapid prototyping. The combination of Moore's Law driving down the cost of computing and the expiration of the patents from the early developments in the 1980s has brought such technology within the reach of the hobbyist or small business.

LASER CUTTING

Although the laser cutter doesn't get the same press attention as the 3D printer, it is arguably an even more useful item to have in your workshop. Three-dimensional printers can produce more complicated parts, but the simpler design process (for many shapes, breaking it into a sequence of two-dimensional planes is easier than designing in three dimensions), greater range of materials which can be cut, and faster speed make the laser cutter a versatile piece of kit.

Laser cutters range from desktop models to industrial units which can take a full 8' by 4' sheet in one pass. Most commonly, though, they are floor-standing and about the same size as a large photocopier.

Most of the laser cutter is given over to the bed; this is a flat area that holds the material to be cut. The bed contains a two-axis mechanism with mirrors and a lens to direct the laser beam to the correct location and focus it onto the material being cut. It is similar to a flatbed plotter but one that burns things rather than drawing on them.

The computer controls the two-axis positioning mechanism and the power of the laser beam. This means that not only can the machine easily cut all manner of intricate patterns, but it can also lower the power of the laser so that it doesn't cut all the way through. At a sufficiently low power, this feature enables you to etch additional detail into the surface of the piece. You can also etch things at different power levels to achieve different depths of etching, but whilst the levels will be visibly different, it isn't precise enough to choose a set fraction of a millimetre depth.

CHOOSING A LASER CUTTER

When choosing a laser cutter, you should consider two main features:

- **The size of the bed:** This is the place where the sheet of material sits while it's being cut, so a larger bed can cut larger items. You don't need to think just about the biggest item you might create; a larger bed allows you to buy material in bigger sheets (which is more cost effective), and if you move to small-scale production, it would let you cut multiple units in one pass.
- **The power of the laser:** More powerful lasers can cut through thicker material. For example, the laser cutter at our workplace has a 40W laser, which can cut up to 10mm-thick acrylic. Moving a few models up in the same range, to one with a 60W laser, would allow us to cut 25mm-thick acrylic.

Depending on what you're trying to create, you can cut all sorts of different materials in a laser cutter. Whilst felt, leather, and other fabrics are easy to cut, for Internet of Things devices you will probably be looking at something more rigid. Card and, particularly, corrugated cardboard are good for quick tests and prototyping, but MDF, plywood, and acrylic (also commonly known by the brand name Perspex) are the most common choices.

Specialised materials are also available for specific purposes. For example, laserable rubber can be used to create ink stamps, and laminate acrylic provides a thin surface in one colour, laminated with a thicker layer in a contrasting colour so that you can etch through the thin layer for crisp, high-contrast detailing and text.

Whilst you are able to get laser cutters which can cut metal, they tend to be the more powerful and industrial units. The lower-powered models don't cut through the metal; and worse, as the shiny surface of many metals does an excellent job of reflecting the laser beam, you run a real risk of damaging the machine. The laser cutters can be used to etch metals, though, if you've carefully prepared the reflective surface beforehand with a ceramic coating compound, such as CerMark. Once coated, either from a spray-can or as tape, the laser will fuse the compound with the underlying metal to leave a permanent dark mark.

If you don't have a laser cutter of your own, there is a good chance that your local makerspace or hackspace will have one that you could use. You might even be able to obtain access to one at a local university or college. Failing that, laser-cutting bureau services somewhat like copy shops are becoming increasingly common. Architects often use these services to help them build architectural models, so that could provide a starting place for your search. If that approach proves fruitless, a number of online providers, such as Ponoko (`http://www.ponoko.com`), let you upload designs that they cut and then post back to you.

SOFTWARE

The file formats or software which you need to use to provide your design vary across machines and providers. Although some laser-cutting software will let you define an engraving pattern with a bitmap, typically you use some type of vector graphics format.

Vector formats capture the drawing as a series of lines and curves, which translate much better into instructions for moving the laser cutter than the grid-like representation of a bitmap. There's also no loss in fidelity as you resize the image. With a bitmap, as you might have seen if you've ever tried blowing up one small part of a digital photo, the details become jagged as you zoom in closely, whereas the vector format knows that it's still a single line and can redraw it with more detail.

CorelDRAW is a common choice for driving the laser cutters themselves, and you can use it to generate the designs too. Other popular options are Adobe Illustrator, as many designers already have a copy installed and are familiar with driving it, and Inkscape, largely because it's an open source alternative and therefore freely available. The *best* choice is the one you're most comfortable working with, or failing that, either the one your laser cutter uses or the one you can afford.

When creating your design, you use the stroke (or outline) of the shapes and lines rather than the filled area to define where the laser will cut and etch. The *kerf*, the width of the cut made by the laser, is about 0.2mm but isn't something you need to include in the design. A thinner stroke width is better, as it will stop the laser cutter from misinterpreting it as two cuts when you need only one.

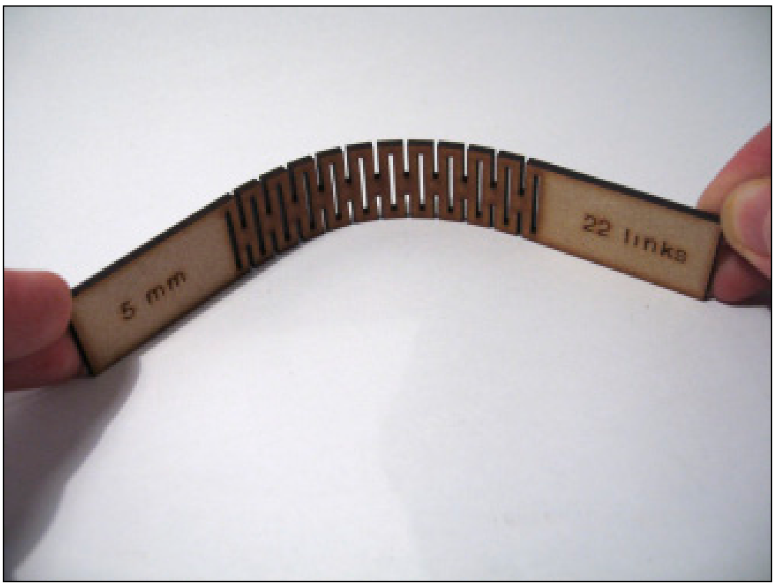
Different types of operation—cut versus etch or even different levels of etching—can usually be included in the same design file just by marking them in different colours. Whoever is doing your cutting may have a set convention of colour scheme for different settings, so you should make sure that you follow this convention if that is the case.

HINGES AND JOINTS

Most of the mechanisms you use to construct items with the laser cutter aren't any different from those used in more general woodwork. A few lesser-known techniques, however, are either easier to achieve with the precision of the laser cutter or have found new popularity after being picked up by this new generation of makers.

Lattice (or Living) Hinges

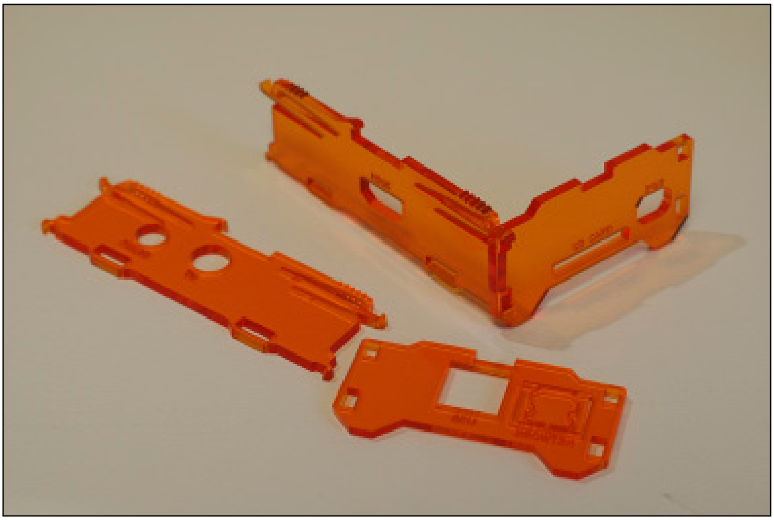
If you're looking to introduce some curves into your design, one of these hinge patterns, reminiscent of the lattice pastry on top of a fruit pie, will do the trick. A series of closely laid-out cuts, perpendicular to the direction of the curve, allows the material to be bent after it has been cut. Varying the number of cuts and their separation affects the resulting flexibility of the hinge. Patrick Fenner has a lovely blog post (`http://www.deferredprocrastination.co.uk/blog/2011/laser-cut-lattice-living-hinges/`) where he digs into how the different parameters affect your results.



The lattice (or living) hinge.

Integrated Elastic Clips

This jointing technique is used in situations similar to a through mortise-and-tenon joint, when joining two sheets of material at 90 degrees. The tenon (tongue) is replaced with two hooks which protrude above and to the side of the mortise, thus holding the mortise sheet tight to the tenon sheet without any need for glue or additional fixings. To provide the required flexibility in the tenon to fit it through the mortise during assembly, additional, deeper cuts are made into the tenon side, as can be seen in the following image. This is another area Patrick Fenner has been exploring on his blog at `http://www.def-proc.co.uk/b/category/def-proc/laser-cut-elastic-clips/`.



Integrated elastic clips.

Bolted Tenon (or T-Slot) Joints

An alternative to integrated elastic clips, the bolted tenon joint is a modified version of the standard mortise-and-tenon joint which adds a T- or cross-shaped slot to the tenon sheet, with the crossbar of the T or cross being just big enough to hold a nut. You can then thread a bolt through a hole in the mortise sheet, down the slot and through the nut.

Bolted tenon or T-slot joint.

Case Study: Nick O'Leary's Ambient Orb

In his spare time, IBM developer Nick O'Leary has been building a multichannel, multicoloured ambient orb to let him keep an eye on things such as his home energy usage.

The orb is controlled via the IBM-developed Message Queueing Telemetry Transport (MQTT) protocol, a way to easily connect outputs (subscribers) to data sources (publishers). Each of the three independently controllable RGB LEDs in the orb is mapped to a different subscription on the MQTT messaging system that he's using. So, for example, if he notices that one side of the orb sitting in his kitchen is glowing red, the reason could be that he's forgotten to turn off the fan heater in his office.

continued

continued

To produce something that would look nice in his home, Nick wanted a design better than a bare circuit board. For the diffuser, he repurposed one from a shop-bought lamp, but as the base needed to hold a completely different circuit board, he designed a new one himself.

He wanted the base to be built out of wood, which ruled out 3D printing and led him towards a laser-cut design with layers of birch plywood stacked on top of each other to achieve the desired height.

Because Nick didn't have immediate access to a laser cutter, his initial designs were done with corrugated cardboard cut out by hand with a craft knife. Using this technique let Nick work out how the layers needed to be laid out in order to accommodate the circuit boards, power connector, and so on, and to come up with a mechanism to bolt the base together. That means he can dismantle the base at a later date for any maintenance or future upgrades.

Ambient Orb bases.

When Nick was happy with the designs, he could get the laser cutting done elsewhere. You can see the cardboard prototype design on the right and two versions of the laser-cut plywood base. There was an additional round-trip in the design when it turned out there wasn't quite enough clearance to let the PCB fit easily, but Nick now has a lovely, professional finish to the design.

For more about the build process, including the source code and PCB design, see `http://knolleary.net/orb/`.

3D PRINTING

Additive manufacturing, or 3D printing as it's often called, is fast becoming one of the most popular forms in rapid prototyping—largely down to the ever-increasing number of personal 3D printers, available at ever-falling costs. Now a number of desktop models, available for less than £500, produce decent quality results.

The term *additive manufacturing* is used because all the various processes which can be used to produce the output start with nothing and *add* material to build up the resulting model. This is in contrast to *subtractive manufacturing* techniques such as laser cutting and CNC milling, where you start with more material and cut away the parts you don't need.

Various processes are used for building up the physical model, which affect what materials that printer can use, among other things. However, all of them take a three-dimensional computer model as the input. The software slices the computer model into many layers, each a fraction of a millimetre thick, and the physical version is built up layer by layer.

One of the great draws of 3D printing is how it can produce items which wouldn't be possible with traditional techniques. For example, because you can print interlocking rings without any joins, you are able to use the metal 3D printers to print entire sheets of chain-mail which come out of the printer already connected together. If only the medieval knights had had access to a metal laser-sintering machine, their armour would have been much easier to produce.

Another common trick with 3D printing is to print pieces which include moving parts: it is possible to print all the parts at the same time and print them ready-assembled. This effect is achieved with the use of what is called "support material". In some processes, such as the powder-based methods, this is a side effect of the printing technique; while the print is in progress, the raw powder takes up the space for what will become the air-gap. Afterwards, you can simply shake or blow the loose powder out of your solid print. Other processes, such as the extruded plastic techniques, require you to print a second material, which takes the supporting role. When the print is finished, this support material is either broken off or washed away. (The support material is specifically chosen to dissolve in water or another solution which doesn't affect the main printing material.)

TYPES OF 3D PRINTING

Lots of innovation is still happening in the world of additive manufacturing, but the following are some of the more common methods of 3D printing in use today:

- **Fused filament fabrication (FFF):** Also known as fused deposition modeling (FDM), this is the type of 3D printer you're most likely to see at a maker event. The RepRap and MakerBot designs both use this technique, as does the Stratasys at the industrial level. It works by extruding a fine filament of material (usually plastic) from a heated nozzle. The nozzle can be moved horizontally and vertically by the controlling computer, as can the flow of filament through the nozzle. The resulting models are quite robust, as they're made from standard plastic. However, the surface can have a visible ridging from the thickness of the filament.
- **Laser sintering:** This process is sometimes called selective laser sintering (SLS), electron beam melting (EBM), or direct metal laser sintering (DMLS). It is used in more industrial machines but can print any material which comes in powdered form and which can be melted by a laser. It provides a finer finish than FDM, but the models are just as robust, and they're even stronger when the printing medium is metal. This technique is used to print aluminium or titanium, although it can just as easily print nylon. MakieLab (discussed in Chapter 9, "Business Models") uses laser-sintered nylon to 3D print the physical versions of its dolls.
- **Powder bed:** Like laser sintering, the powder-bed printers start with a raw material in a powder form, but rather than fusing it together with a laser, the binder is more like a glue which is dispensed by a print head similar to one in an inkjet printer. The Z Corp. machines use this technique and use a print medium similar in texture to plaster. After the printing process, the models are quite brittle and so need post-processing where they are sprayed with a hardening solution. The great advantage of these printers is that when the binder is being applied, it can be mixed with some pigment; therefore, full-colour prints in different colours can be produced in one pass.
- **Laminated object manufacturing (LOM):** This is another method which can produce full-colour prints. LOM uses traditional paper printing as part of the process. Because it builds up the model by laminating many individual sheets of paper together, it can print whatever colours are required onto each layer before cutting them to shape and gluing them into place. The Mcor IRIS is an example of this sort of printer.

- **Stereolithography and digital light processing:** Stereolithography is possibly the oldest 3D printing technique and has a lot in common with digital light processing, which is enjoying a huge surge in popularity and experimentation at the time of this writing. Both approaches build their models from a vat of liquid polymer resin which is cured by exposure to ultraviolet light. Stereolithography uses a UV laser to trace the pattern for each layer, whereas digital light processing uses a DLP projector to cure an entire layer at a time. Whilst these approaches are limited to printing with resin, the resultant models are produced to a fine resolution. The combination of this with the relatively low cost of DLP projectors makes this a fertile area for development of more affordable high-resolution printers.

Deciding which 3D printer to use is likely to be governed mostly by what kind of machine you have ready access to. The industrial-level machines cost tens of thousands of pounds, so most of us don't have the luxury of buying one of them. If you do have that sort of budget, we're jealous; enjoy your shopping!

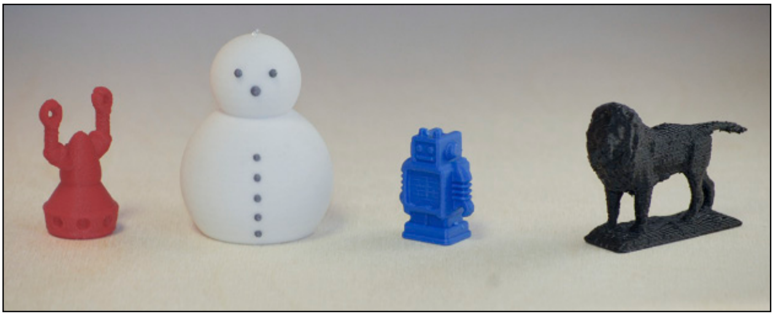
For the rest of us, a few options are available. If you live near to a fab lab or TechShop, they usually have a 3D printer that you are able to use. Similarly, local universities often have such facilities in their engineering or product design departments and might grant you access.

You may also find a local bureau service which will print your designs for you; these services are becoming increasingly common. Recently, Staples announced a service to deliver 3D prints for collection in its stores in the Netherlands.

The Staples announcement is just another, albeit well-known, entrant into the 3D-printing-by-post market. Shapeways (`http://www.shapeways.com/`), i.materialise (`http://i.materialise.com/`), and Ponoko (`https://www.ponoko.com/`) have all been offering similar services for a while now. You upload your design online, choose how you want it printed, and a few days later receive it in the post. Many of these services even facilitate your selling your designs, with them handling the fulfillment for you.

If you don't need the specialist materials or high resolution of the high-end machines, there's a good chance that your local hackspace or makerspace will have one of the lower-cost desktop machines; the pricing of these machines is such that buying one of your own is also an option. In fact, for most prototyping work, one can argue that the greater access and lower cost of materials in that approach far outweigh the disadvantages.

The following image shows some example prints from a few of the more common desktop machines, alongside one from a high-end Z Corp printer for comparison.



Some sample 3D prints: (l– r) MakerBot Replicator; Z Corp.; Ultimaker; RepRap Prusa Mendel.

A huge choice of desktop machines is available these days, thanks mostly to the RepRap project. This initiative was started by Adrian Bowyer back in 2004 with the aim of building a self-*rep*licating *rap*id prototyping machine. Whilst they haven't worked out how to get it to print motors and the like yet, it can print half its own parts. The remaining half are designed to be readily available from a hardware store or online.

The RepRap designs are fully open source, which means that users are free to make their own machines and modify the design to make it better or customise it to suit their particular needs. As a result, there has been a steady evolution in RepRap models—improving the quality of prints and ease of use and lowering the cost of the machines.

This project has also spawned a number of semi-related printers, which share some of the RepRap DNA but have abandoned the self-replicating goal to prioritise other qualities such as robustness or ease of assembly. The best known of these are the MakerBot and Ultimaker machines, which use a laser-cut plywood frame—or in the case of the latest MakerBot models, CNCed steel.

SOFTWARE

In much the same way as for laser cutting, no definitive software package is recommended for use when generating your 3D designs. If you are already familiar with one 3D design program, see whether it can export files in the correct format for the machine you'll use to print. If you are using a printing service, it will advise on which program it prefers you to use or what formats it accepts. Or failing that, choose one to suit your budget and that you find easiest to get to grips with.

Working out how to design items in three dimensions through a two-dimensional display isn't trivial, so it's more important than usual to work through the tutorials for the software you choose. This gives you the best grounding to manipulating objects, ensuring that the components which make up your design line up correctly to minimize the risk of artefacts in the finished print.

Tinkercad (`http://tinkercad.com`) and Autodesk's 123D Design Online (`http://www.123dapp.com/design`) are two options which just run in your web browser. So they let you start designing without having to install any additional software.

Autodesk also has a range of 123D apps available to download and install. You can find a desktop version of 123D Design and also of 123D Catch, a clever application which takes an array of photos of an object and automatically converts them into a 3D model. This inferred 3D model may then need subsequent refinement—for example, with 123D Design.

SolidWorks (`http://www.solidworks.com`) and Rhino (`http://www.rhino3d.com`) are the industry-standard commercial offerings, and SketchUp (`http://www.sketchup.com`), which was owned by Google for a while but in 2012 was sold to Trimble, is popular with hobbyists.

In the open source camp, the main contenders are OpenSCAD (`http://www.openscad.org`) , which has a rather unorthodox scripting workflow, and FreeCAD (`http://free-cad.sourceforge.net`). You also can use Blender (`http://www.blender.org`), but it has a steep learning curve and is better suited to 3D animation than computer-aided design.

When you have your design ready, you need a further piece of software to convert it into a set of instructions which will be fed to the printer. This is usually known as the *slicing algorithm* because its most important function is to carve the model into a series of layers and work out how to instruct the printer to build up each layer. In most cases the particular slicing software that you use is governed by the specific printer which is building your model, but with the open source designs such as RepRap, you might have a couple of options.

Skeinforge was the first slicing software used by the open source printers, but it has been largely overtaken by the newer and more user-friendly Slic3r. Both will let you tweak all manner of parameters to fine-tune your 3D prints, specifying options like the temperature to which the plastic should be heated, how densely to fill the solid objects, the speed at which the extruder head should move, etc.

Getting those settings right (or right enough) can be daunting for the beginner. With its configuration wizard, Slic3r does a much better job of guiding you through to a usable starting point. Running through some calibration tests will let you tailor the settings to your particular printer and the specific plastic that you're printing.

It can feel like a bit of a chore to be printing out 20mm cubes when you're itching to set it going with your great design, but taking some time to set things up when the issues are more easily spotted and remedied will pay back in better quality and more successful prints.

CNC MILLING

Computer Numerically Controlled (CNC) milling is similar to 3D printing but is a *subtractive* manufacturing process rather than *additive*. The CNC part just means that a computer controls the movement of the milling head, much like it does the extruder in an FDM 3D printer. However, rather than building up the desired model layer by layer from nothing, it starts with a block of material larger than the finished piece and cuts away the parts which aren't needed—much like a sculptor chips away at a block of stone to reveal the statue, except that milling uses a rotating cutting bit (similar to an electric drill) rather than a chisel.

Because cutting away material is easier, CNC mills can work with a much greater range of materials than 3D printers can. You still need an industrial-scale machine to work with hardened steel, but wax, wood, plastic, aluminium, and even mild steel can be readily milled with even desktop mills.

CNC mills can also be used for more specialised (but useful when prototyping electronic devices) tasks, such as creating custom printed circuit boards. Rather than sending away for your PCB design to be fabricated or etching it with acid, you can convert it into a form which your CNC mill can rout out; that is, the CNC mills away lines from the metal surface on the board, leaving the conductive paths. An advantage of milling over etching the board is that you can have the mill drill any holes for components or mounting at the same time, saving you from having to do it manually afterwards with your drill press.

A wide range of CNC mills is available, depending on the features you need and your budget.

Sizes range from small mills which will fit onto your desktop through to much larger machines with a bed size measured in metres. There are even CNC mills which fill an entire hangar, but they tend to be bespoke constructions for a very specific task, such as creating moulds for wind turbine blades.

Bigger is not always better, though; the challenges of accurately moving the carriage around increase with their size, so smaller mills are usually able to machine to higher tolerances. That said, the difference in resolution is only from high to extremely high. CNC mills can often achieve resolutions of the order of 0.001mm, which is a couple of orders of magnitude better than the current generation of low-end 3D printers.

Beyond size and accuracy, the other main attribute that varies among CNC mills is the number of axes of movement they have:

- **2.5 axis:** Whilst this type has three axes of movement—X, Y, and Z—it can move only any two at one time.
- **3 axis:** Like the 2.5-axis machine, this machine has a bed which can move in the X and Y axes, and a milling head that can move in the Z. However, it can move all three at the same time (if the machining instructions call for it).
- **4 axis:** This machine adds a rotary axis to the 3-axis mill to allow the piece being milled to be rotated around an extra axis, usually the X (this is known as the *A axis*). An indexed axis just allows the piece to be rotated to set points to allow a further milling pass to then be made, for example, to flip it over to mill the underside; and a fully controllable rotating axis allows the rotation to happen as part of the cutting instructions.
- **5 axis:** This machine adds a second rotary axis—normally around the Y—which is known as the *B axis*.
- **6 axis:** A third rotary axis—known as the *C axis* if it rotates around Z—completes the range of movement in this machine.

For prototyping work, you're unlikely to need anything beyond a 3-axis mill, although a fourth axis would give you some extra flexibility. The 5- and 6-axis machines tend to be the larger, more industrial units.

As with 3D printing, the software you use for CNC milling is split into two types:

- **CAD** (Computer-Aided Design) software lets you design the model.
- **CAM** (Computer-Aided Manufacture) software turns that into a suitable toolpath—a list of co-ordinates for the CNC machine to follow which will result in the model being revealed from the block of material.

The toolpaths are usually expressed in a quasi-standard called *G-code*. Whilst most of the movement instructions are common across machines, a wide variety exists in the codes for things such as initialising the machine. That said, a number of third-party CAM packages are available, so with luck you will have a choice of which to use. For a rundown of the possibilities, along with *lots* more information about getting started with CNC milling, see `http://lcamtuf.coredump.cx/gcnc/`.

REPURPOSING/RECYCLING

So far we've talked just about how you would go about creating a new object completely from scratch. Owning the designs of and knowing how to create all of the components of your device put you in a great position, but they aren't necessarily the overriding concerns in all prototyping scenarios.

As with the other elements of building your connected device, a complete continuum exists from buying-in the item or design through to doing-it-yourself. So, just as you wouldn't think about making your own nuts and bolts from some iron ore, sometimes you should consider reusing more complex mechanisms or components.

One reason to reuse mechanisms or components would be to piggyback onto someone else's economies of scale. If sections or entire subassemblies that you need are available in an existing product, buying those items can often be cheaper than making them in-house. That's definitely the case for your prototypes but may extend to production runs, too, depending on the volumes you'll be manufacturing. For example, the bubble machine used in Bubblino is an off-the-shelf unit from a children's game. In the batch production volumes that Bubblino is currently being built, it's cheaper to buy them, even at retail price, than it would be to manufacture the assorted gears, fans, bubble ring, and casing in-house.

Or perhaps you're making just a couple of units or maybe only one. In that scenario the labour involved in working out how to integrate the electronics, graft in newly fabricated parts, or work out how to disassemble the reused item for the bits you need might not matter, as you aren't going to be repeating it many, many times.

That's often the case with one-off items, when they are deliberately incorporated into existing, mass-produced products. When Russell Davies commissioned Adrian to build him a few minimal-interface WiFi sound boxes (`http://russelldavies.typepad.com/planning/2011/07/secondary-attention-and-the-background-noise.html`), he asked for two separate devices. One was made from scratch with all-new electronics and a laser-cut case, whereas the other was a reworked 1974 transistor radio. The radio circuits were removed to make space for a small ARM Linux board, but the original amplifier was retained and the wave band selector switches were reconfigured to act as the interface to the program. When everything was boxed up, it became a very familiar object but with very new capabilities.

We've drifted away from the idea of prototyping as a way to explore and develop your idea, but that is probably the most common case where reuse and repurposing of existing items are useful.

Given that the prototyping phase is all about rapid iteration through ideas, anything that helps speed up the construction period and gets you to where you can test your theories is useful. When you are thinking through the user interaction of a connected bedside table, for instance, gaffer taping an Arduino to your alarm clock would provide a good-enough approximation to let you try out different scenarios.

If the final design requires processes with massive up-front costs (such as tooling up for injection moulding the plastics) or the skills of a designer that you don't have the funds to hire right now, maybe a product already exists that is near enough to work as a proxy. That lets you get on with taking the project forwards, ending up at a point, one hopes, where making the bigger investment makes sense.

And, of course, it doesn't have to be a finished item that you reuse. The website Thingiverse (`http://www.thingiverse.com`) is a repository of all manner of designs, most of which are targeted at 3D printing or laser cutting, and all available under creative commons licenses which allow you to use the design as is or often allow you to amend or extend it to better suit your own needs.

Case Study: The Ackers Bell

It might be useful to look at a project that Adrian's company, MCQN Ltd., recently completed, especially as it pulls together a number of the themes we've explored in this chapter.

The Ackers Bell is an Internet-connected bell, which was commissioned by the big-data startup ScraperWiki (`http://scraperwiki.com`). It is connected to the company's online billing system and rings the bell whenever a new payment hits its bank account, giving the sales team further incentive to make more sales and everyone else a chance to celebrate every success.

That pretty much covers the project brief—now onto the design and implementation! Casting a bell from scratch was always going to be a stretch, so the first step was to investigate what bells could be sourced elsewhere and reused.

continued

continued

An initial discussion with a campanologist friend quickly found some very nice tuned bells, but sadly they were outside the available budget. After that, they looked at boxing-ring-style bells and at giving a new life to some vintage telephone bells. Both of these types appealed as they'd include both mechanical and electrical striking mechanisms. However, liaising with the customer on the choice led to their settling on a traditional brass ship's bell, which resonated more with ScraperWiki, due to its, and Adrian's, location in the port city of Liverpool.

With the bell procured, the next step was to work out how to mount it. The electronics were relatively easy to develop, given MCQN Ltd.'s experience, and an Arduino Ethernet board married to a solenoid was soon firing when triggered by events online. They just needed to devise a way to assemble the two parts: electronics and bell.

The following photo shows some of the initial sketches made in Adrian's Moleskine notebook, exploring possible ways to construct the housing and some detail of a possible joint design.

Early design ideas for the Ackers Bell.

They thought wood made the best choice of material to complement the brass of the bell but also wanted a darker wood than the stock birch ply we normally use in the laser cutter. In addition, the potential joint design would require wood a fair bit thicker than the 3mm ply, so they finally chose an 8mm thick oak from the range of hardwoods at the local timber merchant.

Unfortunately, some test cuts—or more accurately, test burns—showed that the oak was too hard for either of the readily available laser cutters to manage. Further experimentation was required.

For the choice of wood, they tried a variety of different veneers and also some stains and waxes on the birch ply. In the end, a dark beeswax on the birch ply gave a good colour with the added benefit of some protection and treatment for the wood.

As to how the wood would be used, that issue was solved by Ian Scott, a product design student from Liverpool University who was spending some time at the company on an internship. He came up with the idea of housing the bell inside a lattice framework of stock 3mm ply, shaped to echo the lines of the bell itself. That design meant that although the final form was a fairly complex three-dimensional design, it could be constructed from flat sheets of wood cut on the laser cutter.

In addition to providing a support to hang the bell, the laser-cut design included a platform to hold the Arduino board and a mounting point for the solenoid—cleverly hidden inside the bell to keep the external profile clean. However, the particular solenoid Adrian had chosen didn't have anything to arrest the travel of the striking pin when it is deactivated, so after the first firing, the return spring would cause it to fall out.

While they could no doubt have laser cut some sort of baffle, they decided that the 3D printer allowed them to fabricate a neater solution. Ian designed a relatively simple, L-shaped part which used the same mounting holes as the solenoid itself and provided a wall of black ABS plastic to keep the striking pin in check.

The final stage in the design work was positioning the solenoid so that it gave a clear and consistent chime from the bell. A bell which looks great but sounds awful is no use at all.

They had tested it earlier and included some room for adjustments in the mounting point, but when everything was assembled properly, it was apparent that they hadn't tested it well enough. Sometimes they'd get a crisp, resonating tone, but frequently the striker would either hardly strike the bell at all, or it would strike the bell with such force that the bell would swing back into the solenoid after firing and damp the sound.

This situation would have been much easier to remedy had they iterated through more options for mounting the solenoid when first designing the frame. Solving the problem this late in the build, when the scope for changes was smaller, meant lots of time was wasted trying things such as increasing the power supplied to the solenoid or working out how to alter the mounting point while keeping the existing one in place.

continued

continued

Eventually, they fashioned a shim which adjusted the angle at which the solenoid struck the bell, to make it perpendicular to the bell's surface at the point of impact. You'll have to take our word for it that it now sounds great, but at least we can show you how good it looks.

The Ackers Bell, ready for delivery to the customer.

SUMMARY

This chapter (and the previous one) provided you with a good grounding in building your Internet of Things device.

Some design iteration and exploration will have given you a better understanding of how the form and size of the design affect how it fits in with its use in people's lives, and that learning might well be evidenced in a succession of prototypes cluttering up your workshop.

In addition to showing the progression of the thinking behind the design, the prototypes will show a progression of refinement as you move from the foamcore or cardboard mockups through to sturdier and more polished versions created using some of the rapid prototyping tools like the laser cutter or 3D printer.

With the device side of your prototype covered, all that remains to complete your Internet of Things product is some online service for it to communicate with. The next chapter will take you through that, looking at how you can talk to existing online services or develop something completely new.